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Observations of the x-ray source 4U 1700—37: results from the WATCH instrument on the Granat observatory

S. Yu. Sazonov, I. Yu. Lapshov, and R. A. Syunyaev

Space Research Institute, Russian Academy of Sciences, Moscow

S. Brandt, N. Lund, and A. Castro-Tirado

Space Research Institute, Lyngby, Denmark

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The x-ray source 4U 1700—37 was observed with the WATCH instrument on the Granat observatory between September 1991 and October 1992. We present the results of those observations here. We find that the orbital period of the binary is decreasing at a rate $\dot{P}/P = -(4.13 \pm 0.19) \times 10^{-6}$ yr^{-1}. We present light curves which illustrate that the x-ray flux from the source is highly variable on various time scales. In the energy range 8–60 keV, the light curves of 4U 1700—37 are essentially symmetric about phase 0.5.

Introduction. Among the many x-ray binaries which have been discovered up to the present time, one class that stands out is the high-mass binaries, which contain an accreting neutron star or black hole and a massive early type star (O–B). One of the most thoroughly studied objects in this class is 4U 1700 − 37/HD 153919. The behavior of the x-ray source 4U 1700 − 37 was first described by Jones et al. (1973). It was discovered that the source is in a binary with orbital period $3^d.412$. The optical companion is an O6f star (conti and Cowley, 1975). The distance to the system is estimated to be 1800 pc (Conti, 1978). Up to the present time, no pulsations have been detected in the x-ray flux, although the mass function (Hutchings, 1974) and source spectrum (Haberl et al., 1989) suggest that 4U 1700 − 37 is an accreting neutron star. Especially noteworthy is the fact that the orbital period of the binary is decreasing rapidly with a time-scale of $\sim 10^5$ yr. The latter value was determined by Haberl et al. (1989) from an analysis of times of mid-eclipse obtained by various investigators in different years.

In the present article, we present some observations of 4U 1700 − 37 by the WATCH instrument on the Granat satellite. The data we have reduced span a long period of time (more than a year). This makes it possible for us to study the behavior of the source on various time scales, and also to obtain averaged information about the orbital properties of the system. There is a long gap (about seven years) separating our observations from those of EXOSAT (Haberl et al., 1989), and as a result, we can check the hypothesis concerning the speeding up of the binary rotation.

The x-ray source 4U 1700 − 37 was observed with the WATCH instrument, one of the instruments which was put into orbit as a component of the Granat observatory. WATCH consists of four x-ray detectors equipped with rotating collimators (Lund, 1986; Mertz, 1968). At the present time, three detectors are operating, each with a field of view of about 4 sr, and an effective area of 45 cm^2 for a source on the optical axis. The detectors operate in the energy range 8-60 keV, and this is divided into two subranges: 8-20 and 20-60 keV.

Between September 1991 and October 1992, the source passed through the field of view of each detector many times. Our observations show that the flux from the source is highly variable on time scales ranging from hours to months. The light curve for the source over the entire observing period is presented in Fig. 1 (in the energy range 8-20 keV).

The x-ray flux curve in each detector has been normalized to the corresponding flux from the Crab nebula. Each point in Fig. 1 was obtained by averaging the observations over approximately 2 days. In order to exclude the times of x-ray eclipse (when the flux from the source essentially disappears), we have included in the averages only points with orbital phases 0.3-0.7. Throughout our observations, the mean flux of 4U 1700 − 37 outside eclipse was 300 mCrab in the energy range 8-20 keV and 190 mCrab in the range 20-60 keV. We should point out that the hardness of the radiation from the source remains constant (within the error bars) when the source is in different states. (The hardness is defined to be the ratio of the fluxes in the hard and soft energy ranges.) In Fig. 2 we present one of the brightest outbursts (April 1992) of 4U 1700 − 37 during the entire period which we are describing.

The horizontal bars indicate calculated times of eclipse. In preparing the figure, we have used the following ephemerides: time of mid-eclipse JD 2446161.340 ± 0.003, orbital period $3^d.411652 \pm 0^d.000026$, duration of x-ray eclipse $0^d.843 \pm 0^d.011$ (Haberl et al., 1989). From the light curve, besides rapid irregular variations in the flux, we also see smooth increases in intensity lasting for several orbits of the system, and analogous declines in the flux. During this outburst, maximum flux was reached on 12 April 1992: it amounted to 1300 milliCrab in the energy range 8-20 keV.

Orbital light curve. To find the ephemeris of an eclipsing binary, the major difficulty is to determine the times when the x-ray eclipse starts and ends. In the case of 4U 1700 − 37/HD 153919, the situation is even more complicated because the flux from the source is highly variable. Because of this, in order to find the epoch of mid-eclipse in x rays, and the duration of the eclipse, we have used averaged orbital light curves of the source. One of these phase functions is shown in Fig. 3. In preparing Fig. 3, we used the same ephemerides as for Fig. 3. The entire orbital period was divided into 70 bins, and in each, we averaged the data in that phase bin. The data were averaged over an interval of approximately one year (i.e., almost the entire period of

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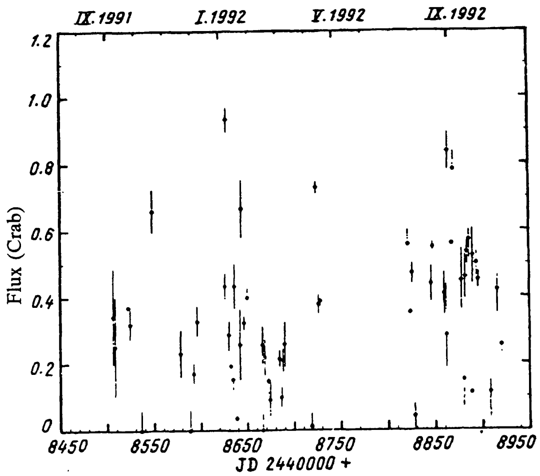

FIG. 1. Light curve of 4U 1700 − 37 in the energy range 8-20 keV between September 1991 and October 1992.

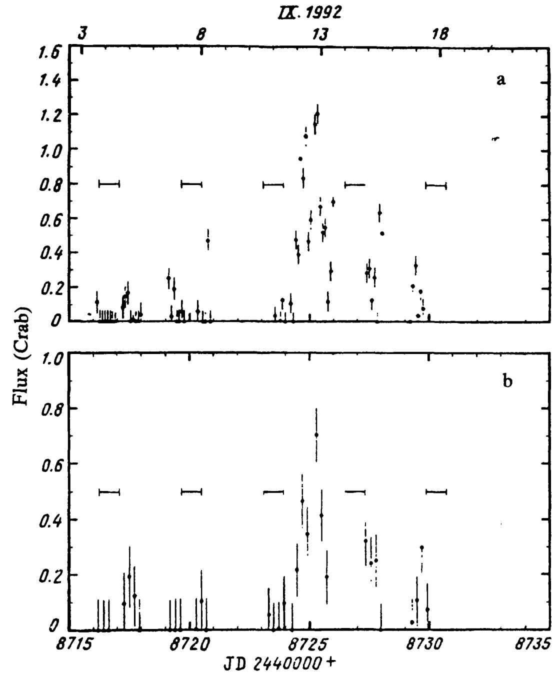

FIG. 2. Light curve of the source during an outburst in April 1992. Each point was obtained by averaging a) ~2.5 hours of observing in the range 8-20 keV, and b) about 5 hours in the range 20-60 keV. Horizontal bars denote the calculated times of eclipse (according to the ephemeris given in the text).

observations). The length of a single phase bin in Fig. 3 is slightly more than one hour. It turned out that on this sort of time scale, the decrease in flux as the source goes into eclipse can be well described by a first-degree polynomial. We reckoned the instant at which the system went into eclipse as the point where a straight line (approximating the fall-off in flux) intersected the mean noise level during eclipse. An analogous procedure was used to derive the instant when the system came out of eclipse. Uncertainties in these estimates are due mainly to the value of the flux during eclipse and the rate at which the source enters into (or comes out of) eclipse. We have analyzed the light curve in Fig. 3 according to these criteria, and have obtained the following results: the mean flux during eclipse is 23 ± 11 mCrab; the eclipse begins at orbital phase 0.882 ± 0.013, and ends at orbital phase 0.088 ± 0.012; and mid-eclipse occurs at orbital phase 0.985 ± 0.009. Here, and in what follows, the errors which we quote in the parameters are one standard deviation. Note that the flux during eclipse is not zero. In this regard, we need to place special emphasis on one reason why it is difficult to observe the source: 4U 1700 − 37 lies within 1°.5 of the bright transient source 4U 1702 − 36. Although the resolution of the WATCH instrument is ~0°.5, we cannot rule out a small contribution from 4U 1702 − 36 to the flux of 4U 1700 − 37 during eclipse. There is no doubt, therefore, that the presence of x-ray flux during eclipse must be corrected for. But this will require instruments with better angular resolution than WATCH.

As a check on the validity of the results, we performed an analogous analysis of the orbital light curves with different binnings. Within the error bars, the results are in agreement with those presented above. We should point out that decreasing the bin size does not improve the precision of the results. The reason is that each point on the phase curve is obtained by averaging over a smaller number of observations, and this leads to an increase in the uncertainty. Therefore, the binning into approximately 70 intervals turns out to be optimal. We obtain the following epoch of mid-eclipse: JD 2448723.440 ± 0.031, and the duration of the eclipse is $0^d.71 \pm 0^d.06$, or 0.206 ± 0.018 in overall orbital phase. The epoch of mid-eclipse presented here has been taken near the middle of the period of the observations which entered into the averages. In Table I, we present our results along with those of other workers. Data in the table were taken from papers by Jones et al. (1973), Branduardi et al. (1978), Dolan et al. (1980), Kudryavtsev and Svertilov (1991), and Haberl et al. (1989). One of the main features of the observations of the x-ray binary 4U 1700 − 37 is that there are large variations in the eclipse duration. This can be seen in Table I. In Fig. 4 we present the observed duration of eclipses as a function of photon energy. There are large uncertainties in determining the onset and end of an eclipse. Despite this, we notice a tendency for the eclipse durations to decrease with increasing energy of the photons which we are using. The durations are ~0.5 days in hard x rays, and they vary between ~0.6 and 1.1 days in soft x rays. The value which we have derived is consistent with the results of previous experiments. Unfortunately, our measurements are not precise enough to allow us to search for possible periodicity in the eclipse durations in this system (Khruzina and Cherepashchuk, 1983).

The epochs of mid-eclipse which we have derived in this experiment (as well as others in Table I) have been used to derive an ephemeris for the system. In our fitting process, we excluded 1974 data from Copernicus: these data were not used in the calculations of Haberl et al. (1989) or Branduardi et al. (1978). When we use a first-order polynomial approximation, we obtain the following results: epoch of mid-eclipse = JD 2448723.539 ± 0.004; period = $3^d.4117212 \pm 0^d.0000038$. This solution yields $\chi^2 = 18.1$ with 5 degrees of

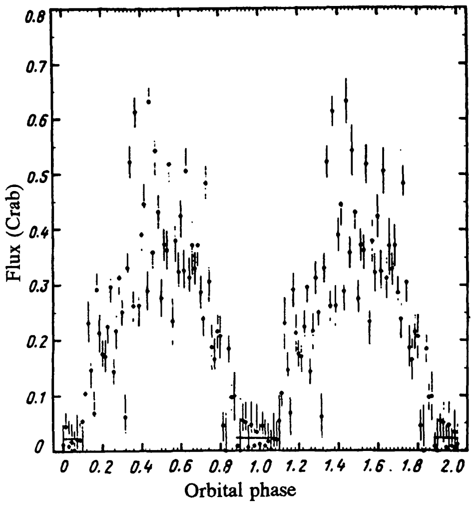

FIG. 3. Orbital phase curve of 4U 1700 − 37. The orbital cycle has been divided into 70 bins. Horizontal lines indicate times of eclipse obtained by a fitting technique (see text). The lines have been drawn at a level corresponding to the flux during eclipse.

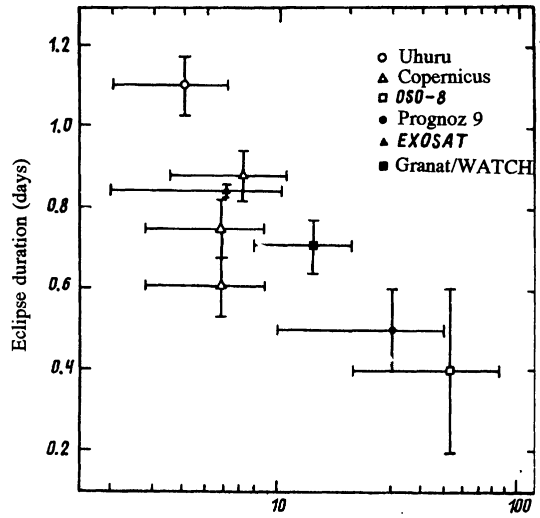

FIG. 4. Observed duration of eclipses as a function of photon energy. Data taken from various experiments.

freedom. When we fit the same points with a quadratic function, χ^2 falls to 1.9 with 5 degrees of freedom. This is entirely acceptable. When the epoch of mid-eclipse is approximated by a quadratic function, it means that the orbital period is changing at a constant rate. The time of mid-point of the nth eclipse is given by

$$T_n = T_0 + Pn + \tfrac{1}{2}P\dot{P}n^2,$$

where P and $\dot{P}$ are the orbital period and its first derivative respectively at time T_0. We have obtained the following results:

$$T_0 = \mathrm{JD}\ 2448723.448 \pm 0.005;$$

$$P = 3^{d}.411548 \pm 0^{d}.000005;$$

$$\tfrac{1}{2}P\dot{P} = -(6^{d}.6 \pm 0^{d}.3)\cdot 10^{-8};$$

$$\dot{P} = -(3^{d}.87 \pm 0^{d}.18)\cdot 10^{-8};$$

$$\dot{P}/P = -(1.13 \pm 0.05)\cdot 10^{-8}\ \mathrm{day}^{-1} = -(4.13 \pm 0.19)\cdot 10^{-6}\ \mathrm{year}^{-1}$$

The delay between the epoch of mid-eclipse and the value estimated by assuming a constant period for the binary is shown as a function of time in Fig. 5. Also shown in Fig. 5 is the parabolic fit to the experimental points. The value we have derived for the rate of period decrease is in agreement with the value obtained from EXOSAT (Haberl et al., 1989), when the reduction in the orbital period of this system was first noted. To derive errors in the orbital parameters, we have allows for the fact that the observational data from the WATCH instrument have been summed in time over ~100 orbits. To obtain the errors, we carried out the fit while varying the epoch of mid-eclipse by up to ~50 orbits on one side or the other relative to the epoch we have derived.

In Fig. 6 we present orbital light curves for the source in various energy ranges using 20 bins per orbital cycle. Also shown in Fig. 6 is the spectral hardness of the source as a function of phase. The hardness is defined to be the ratio of flux in the 20-60 keV range (in units of the flux of the Crab nebula) to the flux in the 8-20 range keV (in the same units). The zero point in phase in Fig. 6 corresponds to the epoch of mid-eclipse which we have derived. We should mention that the number of points averaged in each bin (about 25) is roughly four times larger in Fig. 6a) than in Fig. 6b. The reason is that the light curves in the 20-60 keV range were constructed from a shorter period of time. Moreover, in most

TABLE I. Observations of 4U 1700 − 37

Observations		Energy range (keV)	Eclipse duration (days)	Epoch of mid-eclipse (JD 2440000+)
Uhuru	1972	2—6	1.10 ± 0.07	1453.14
Copernicus	1974	3.5—10.7	0.88 ± 0.06	2231.125
	1975	2.8—8.7	0.61 ± 0.07	2609.750 2613.146
	1976	2.8—8.7	0.75 ± 0.07	3002.104 3005.500
OSO-8	1978	21—84	~0.4	
Prognoz 9	1983—1984	10—50	~0.5	
EXOSAT	1985	2—10	0.843 ± 0.011	6161.340
WATCH	1991—1992	8—20	0.71 ± 0.06	8723.44

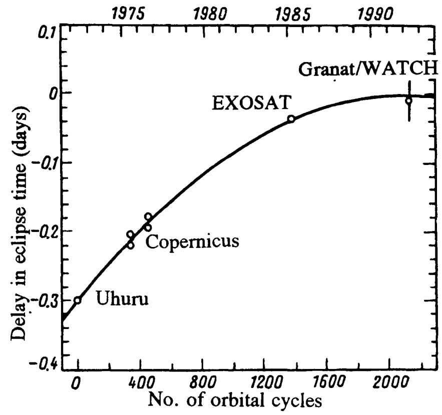

FIG. 5. Deviation of epoch of mid-eclipse from the value estimated from a linear ephemeris $T_n = 2441453.439 + 3.411548n$ as a function of the number n of orbital cycles. Solid curve: quadratic approximation.

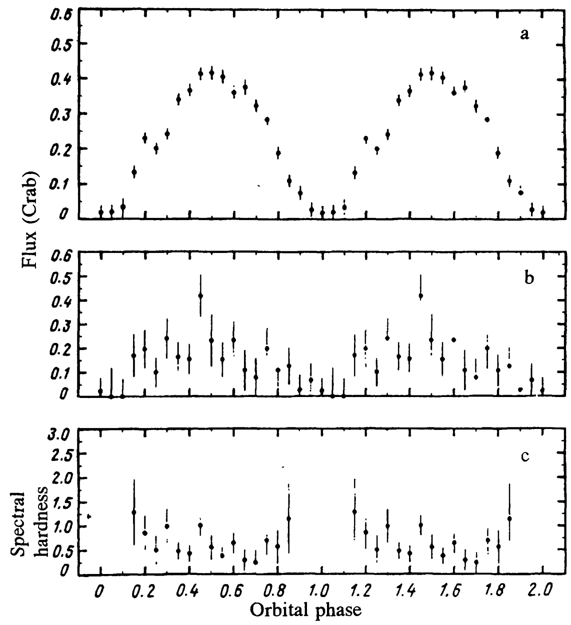

FIG. 6. X-ray flux as a function of orbital phase at energies of a) 8-20 keV and b) 20-60 keV; c) spectral hardness of the source.

scans, the integration time in the 20-60 keV range was chosen to be twice as long as in the 8-20 keV range. Because we have such a large number of observations to average, we can verify that the phase dependence illustrated in Fig. 6 must be due mainly to the properties of the orbital motion in this system. A striking feature of all of the orbital curves in Fig. 6 is that they are approximately symmetric about orbital phase 0.5. In this regard, there is a difference between the behavior of the system at WATCH energies and its behavior at energies below 10 keV. In the latter case, the increase in flux from the source as the system energies from eclipse is typically faster than the decline, and there is a sharp increase in the spectral hardness before the system enters into eclipse (Branduardi et al., 1978; Haberl et al., 1989). From Fig. 6c, we can see that the spectral hardness over the 8-60 keV range independent of orbital phase (within the error bars). There is some increase in the hardness prior to onset of eclipse, and after emergence from eclipse, but the significance is not great.

Discussion. Long-duration observations of the x-ray source such as Cyg X-1, Vel X-1, Cen X-3, and GX 301 − 3, which was also observed by WATCH (Castro-Tirado et al., 1993; Chichkov et al., 1993). The fact that the orbital light curves are smooth and symmetric indicates that in 4U 1700 − 37, we are dealing with modulation of the x-ray flux by the stellar wind flowing from the surface of the normal component. In the energy range of the WATCH instrument, Compton scattering by electrons dominates the opacity in tenuous plasma. Therefore, since the flux changes smoothly as the source goes into and comes out of eclipse, it means that the wind has considerable optical depth to Thomson scattering. In the context of a stellar wind model, it is also possible to explain the tendency mentioned above, viz., the eclipse duration decreases as the photon energy increases. Less energetic photons are efficiently absorbed by the stellar wind: this leads to the observed effect (an increase in the phase of eclipse). Stellar wind modeling for 4U 1700 − 37 can be found in the article by Sazonov et al. (1993).

One of the most important results obtained by the WATCH instrument is to confirm the fact that the period of the binary is decreasing at a very rapid rate: $\dot{P}/P = -(4.13 \pm 0.19)\cdot 10^{-6}$ year^{-1}. An analogous change in period has also been seen in Cen X-3, although the rate is slower: $\dot{P}/P = -(1.8 \pm 0.1)\cdot 10^{-6}$ year^{-1}. Kelley et al. (1983) have presented a detailed analysis of two possible reasons for the decreasing period in Cen X-3. The first has to do with mass loss from the optical component (e.g., by means of a stellar wind) which causes a redistribution of angular momentum in the system. The second has to with the effects of tidal forces. We have applied the results of Kelley et al. (1983) to 4U 1700 − 37, and we can state with confidence that the observed magnitude and sign of the period change cannot be explained if the optical component is losing mass at a rate of $\sim 10^{-5}\ M_{\odot}\cdot$yr^{-1} [e.g., Conti (1978)]. Suppose the change in the period of the system is due to tidal interactions. Then in order to explain the rate of period change which we have obtained, we require $(\Omega_k - \Omega_c)/\Omega_k \sim 20\%$. Here, Ω_k is the orbital angular velocity, and Ω_c is the angular velocity of the optical component. In these estimates, we have taken the system parameters from Conti (1978). Actually, earlier observations have shown that the rotation rate of HD 153919 is roughly half the value required for synchronous rotation with the orbit of the x-ray source (Conti, 1978). We therefore conclude that tidal effects play the major role in the observed variations of orbital period.

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Observations of a cosmic gamma-ray burst on 23 July 1992 with the WATCH instrument on the *Granat* observatory

O. V. Terekhov, V. A. Lobachev, D. V. Denisenko, I. Yu. Lapshov, and R. A. Syunyaev

Space Research Institute, Russian Academy of Sciences, Moscow

N. Lund, A. Castro-Tirado, and S. Brandt

Space Research Institute, Lyngby, Denmark

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The cosmic gamma-ray burst detected by the *Granat* observatory on 23 July 1992 at $20^h03^m08^s.377$ (UT) is one of the brightest events observed during its operation, beginning in December 1989. That burst was detected by three burst instruments on the observatory (PHEBUS, SIGMA, and WATCH). Below we give data from the WATCH Russian–Danish experiment on locating the source of the burst, the light curve in various energy ranges, and the evolution of the hardness of the radiation. We show that the source of the gamma-ray burst emitted a fading x-ray flux with a characteristic temperature ~5 keV, in the approximation of a blackbody spectrum, for more than 40 sec after the burst ended in hard x rays. We give the limits on the luminosity of a steady source at the site of the burst in the 8–20 keV range. We show that the flux from a steady source at the site of the burst did not exceed 20 mCrab for at least several days before and after the event.

INTRODUCTION

The WATCH instrument, designed to monitor bright x-ray sources and observe x-ray transients, solar flares, and cosmic gamma-ray bursts, is part of the *Granat* space observatory. The *Granat* satellite was inserted into a high-apogee orbit on 1 December 1989. The instrument consists of four x-ray detectors, each of which has a rotating modulation collimator located above a mosaic scintillation crystal consisting of alternating bands of NaI(Tl) and CsI(Tl) crystal detectors. The energy range of the detected gamma rays is 8-180 keV. The geometrical area of the mosaic crystal is 48 cm^2. The instrument was developed and built at the Danish Space Research Institute. The instrument has been described in more detail by Lund (1992).

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LOCATION OF THE SOURCE

Thanks to the rotating collimator, the WATCH instrument can determine the coordinates of x-ray sources and bright cosmic gamma-ray bursts. The rotation rate of the modulation collimator is 1 rps. From the modulation pattern resulting from the integration of pulses during rotation of the collimator, one can uniquely determine the coordinates of a gamma-ray burst. To locate the source reliably, three conditions must be satisfied simultaneously: a) the gamma-ray burst must be sufficiently intense; b) the duration of the gamma-ray burst must exceed 1 sec; c) the light curve must be sufficiently smooth and contain no bright features lasting much less than 1 sec.

All of those conditions were satisfied for the event under consideration. The location of the source based on the WATCH data is given in Fig. 1. It coincides with the coordi-

